METEOROLOGISK INSTITUTT
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Transboundary air pollution by main pollutants (S, N, O$_3$) and PM in 2010

Germany

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Contents

1 How to read this report

This report is one of a series of country-specific notes, complementary to the EMEP Status Report 1/2012. It presents an overview of transboundary pollution of main pollutants, ground level ozone and particulate matter (PM) for Germany in 2010.

All model runs have been performed with the EMEP/MSC-W model version rv4, using ECMWF-IFS meteorology. The transboundary contributions presented here are based on source-receptor calculations with the EMEP/MSC-W model using meteorological and emission data for the year 2010.

As a basis for their correct interpretation, this section briefly explains what types of results are shown in this report and how they have been calculated.

1.1 The chapters of this report

Emissions *(Chapter 2)* : The emissions for 2010 have been derived from the 2012 official data submissions to UNECE CLRTAP. The gridded distributions of the 2010 emissions have been provided by the EMEP Centre on Emission Inventories and Projections (CEIP). More detailed information on 2010 emission data is provided in the EEA/CEIP Report *"Inventory Review 2012"*.

The emissions for the period of 2000–2010 have been derived from the latest data submissions to UNECE CLRTAP as of May 2012. Consequently, for these years both the gridded emission data and the national and sector totals might differ from those which were used in previous EMEP reports. The spatial allocation of the emission data is, in general, based on the original base grid distribution of the particular year. If this was not available, the distribution from the most recent base grid was applied for the re-gridding of historical emission data.

All model calculations were carried out for the extended EMEP domain. However, expert estimates for the extended domain are available only from year 2007. For those areas where no historical data are given in the EMEP emission inventory, the 2007 gridded emissions were used for the years 2000–2006.

The re-gridded emission data used in the model calculations this year are available on WebDab: `http://www.emep-emissions.at/emission-data-webdab/`.

Trends *(Chapter 3)* : Trends in depositions and air concentrations are presented for the period of 2000–2010. The calculations are based on a consistent series of model runs, all using the EMEP/MSC-W model version rv4. For the years 2000–2010, the meteorology of the respective year is used. This was possible for the first time this year as a consistent set of ECMWF-IFS meteorology for the entire 2000–2010 period has become available to MSC-W. The trend figures also show depositions and air concentrations for 2020, based on a model simulation that uses emission projections for 2020 from the revised Gothenburg Protocol. The model simulation for 2020 uses year 2005 meteorology (because 2005 is the base year of the Protocol). It also uses CO emissions for 2005 (because CO emissions are not projected for 2020 in the Protocol). The results for 2020 have thus to be compared to those for 2005.

Transboundary fluxes and concentrations *(Chapters 4-6)* : Data are presented in the form of maps, pies and bar charts. The data are generated by source-receptor calculations, where emissions for each emitter of one or more precursors are reduced by 15%. For oxidised sulphur, oxidised nitrogen and reduced nitrogen, the results have been scaled up to represent the entire emission from an emitter. For other components, which are subject to

significant non-linearities, we present the effect of a 15% reduction only. To give more intuitive pictures on the effect of pollution from a given country, we use positive scales in the maps for pollution reductions. Negative values thus mean an increase of pollution levels.

The pie charts give a picture of the relative contributions from different countries or regions to depositions and concentrations over Germany.

For O_3 and related indicators bar charts are used because in some cases the effect of a reduction of emissions from a country can either increase or decrease O_3 levels elsewhere. The values in the bar charts for ozone indicators show the six most important contributors to AOT40, ozone fluxes and SOMO35 in Germany. Since the contributions can be both positive or negative, the relative importance of each contributor has been determined by comparing the absolute values of the contributions.

Comparison with observations *(Chapter 7)* : The map of monitoring stations shows stations of Germany in the EMEP measurement network with measurements in 2010 submitted to EMEP. The frequency analysis plots compare daily observation results with the model results. The measurement data are available from CCC: `http://www.nilu.no/projects/ccc/emepdata.html`. The table provides annual statistics of the comparison of model results with observations for each measured component. Comparison is done only for stations with a sufficiently consistent set of data available in weekly or higher time resolution.

Risks from ozone and PM *(Chapter 8)* : The maps of ozone and PM values correspond to regional background levels and they are not representative of local point measurements, where these values can be much higher (i.e. in cities).

NOTE: In this series of country reports, trends are also presented for Kyrgyzstan, Uzbekistan, Turkmenistan and Tajikistan, although, as mentioned above, historical emission data before 2007 are not available. Emissions used for the years 2000–2006 are thus the same as for 2007 for these countries. The presented inter-annual changes of depositions and air concentrations are induced by the emission changes in the old EMEP domain (132×111 grid cells) only.

For the Russian Federation and Kazakhstan, trends refer to the area of these countries inside the extended EMEP domain (132×159 grid cells), now covering all of Kazakhstan's territory and a larger part of the Russian Federation.

1.2 Country codes

Many tables and graphs in this report make use of codes to denote countries and regions in the EMEP area. Table 1 provides an overview of these codes and lists the countries and regions included in the source-receptor calculations for 2010.

Code	Country/Region	Code	Country/Region
AL	Albania	IE	Ireland
AM	Armenia	IS	Iceland
AST	Asian Areas, extended EMEP domain	IT	Italy
AT	Austria	KG	Kyrgyzstan
ATL	Remaining North-East Atlantic Ocean	KZT	Kazakhstan in the extended EMEP domain
AZ	Azerbaijan	LT	Lithuania
BA	Bosnia and Herzegovina	LU	Luxembourg
BAS	Baltic Sea	LV	Latvia
BE	Belgium	MD	Republic of Moldova
BG	Bulgaria	ME	Montenegro
BIC	Boundary and Initial Conditions	MED	Mediterranean Sea
BLS	Black Sea	MK	The former Yugoslav Republic of Macedonia
BY	Belarus	MT	Malta
CH	Switzerland	NL	Netherlands
CY	Cyprus	NO	Norway
CZ	Czech Republic	NOA	North Africa
DE	Germany	NOS	North Sea
DK	Denmark	PL	Poland
DMS	Natural Marine Emissions	PT	Portugal
EE	Estonia	RO	Romania
ES	Spain	RS	Serbia
EU	European Union (EU27)	RUE	Russian Federation, extended EMEP domain
EXC	EMEP land areas (extended)	SE	Sweden
FI	Finland	SI	Slovenia
FR	France	SK	Slovakia
GB	United Kingdom	TJ	Tajikistan
GE	Georgia	TMT	Turkmenistan
GL	Greenland	TR	Turkey
GR	Greece	UA	Ukraine
HR	Croatia	UZT	Uzbekistan
HU	Hungary	VOL	Volcanic emissions

Table 1: Country/region codes used in the source-receptor calculations. 'official' refers to the area of the country/region which is inside the official EMEP grid, while 'extended' refers to the area of the country/region inside the extended EMEP grid.

1.3 Definitions, statistics used

The following definitions and acronyms are used throughout this note:

SIA   denotes secondary inorganic aerosol and is defined as the sum of sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+). In the EMEP/MSC-W model SIA is calculated as SIA= SO_4^{2-} + NO_3^- (fine) + NO_3^- (coarse) + NH_4^+.

SS   - sea salt.

PPM   denotes primary particulate matter, originating directly from anthropogenic emissions. One usually distinguishes between fine primary particulate matter, PPM$_{2.5}$ with dry aerosol diameters below 2.5 μm and coarse primary particulate matter, PPM$_{coarse}$ with dry aerosol diameters between 2.5 μm and 10 μm.

PM$_{2.5}$ denotes fine particulate matter, defined as the integrated mass of aerosol with dry diameters up to 2.5 μm. In the EMEP/MSC-W model PM$_{2.5}$ is calculated as PM$_{2.5}$ = SO_4^{2-} + NO_3^- (fine) + NH_4^+ + SS(fine) + PPM$_{2.5}$ + 0.27 NO_3^- (coarse).

PM$_{coarse}$ denotes coarse particulate matter, defined as the integrated mass of aerosol with dry diameter between 2.5μm and 10μm. In the EMEP/MSC-W model PM$_{coarse}$ is calculated as PM$_{coarse}$ = 0.73 NO_3^- (coarse)+ SS(coarse) + PPM$_{coarse}$.

PM$_{10}$ denotes particulate matter, defined as the integrated mass of aerosol with dry diameters up to 10 μm. In the EMEP/MSC-W model PM$_{10}$ is calculated as PM$_{10}$ = PM$_{2.5}$ + PM$_{coarse}$.

SOMO35   is the Sum of Ozone Means Over 35 ppb is an indicator for health impact assessment recommended by WHO. It is defined as the yearly sum of the daily maximum of 8-hour running average over 35 ppb. For each day the maximum of the running 8-hours average for O$_3$ is selected and the values over 35 ppb are summed over the whole year.

If we let A_8^d denote the maximum 8-hourly average ozone on day d, during a year with N_y days (N_y = 365 or 366), then SOMO35 can be defined as:

$$SOMO35 = \sum_{d=1}^{d=N_y} \max\left(A_8^d - 35 \text{ ppb}, 0.0\right)$$

where the max function ensures that only A_8^d values exceeding 35 ppb are included. The corresponding unit is ppb·days (abbreviated also as ppb·d).

AOT40   is the accumulated amount of ozone over the threshold value of 40 ppb, i.e.:

$$AOT40 = \int \max(O_3 - 40 \text{ ppb}, 0.0)\, dt$$

where the max function ensures that only ozone values exceeding 40 ppb are included. The integral is taken over time, namely the relevant growing season for the vegetation concerned, and for daytime only. The corresponding unit is ppb·hours (abbreviated to ppb·h).

Although the EMEP model generates a number of AOT-related outputs, in accordance with the recommendations of the UNECE Mapping Manual we will concentrate in this report on two definitions:

AOT40$_f^{\text{uc}}$ - AOT40 calculated for forests using estimates of O$_3$ at forest-top (*uc*: upper-canopy). This AOT40 is that defined for forests by the UNECE Mapping Manual, but using a default growing season of April-September.

AOT40$_c^{\text{uc}}$ - AOT40 calculated for agricultural crops using estimates of O$_3$ at the top of the crop. This AOT40 is close to that defined for agricultural crops by the UNECE Mapping Manual, but using a default growing season of May-July, and a default crop-height of 1 m.

POD$_Y$ - Phyto-toxic ozone dose, is the accumulated stomatal ozone flux over a threshold Y, i.e.:

$$\text{POD}_Y = \int \max(F_{st} - Y, 0)\, dt \qquad (1)$$

where stomatal flux F_{st}, and threshold, Y, are in nmol m^{-2} s^{-1}, and the $\texttt{max}$ function evaluates $\max(A - B, 0)$ to $A - B$ for $A > B$, or zero if $A \leq B$. This integral is evaluated over time, from the start of the growing season (SGS), to the end (EGS).

For the generic crop and forest species, the suffix "gen" can be applied, in this report e.g. POD$_{1.0,\text{gen-DF}}$ (or AF$_{st}$1.6$_{\text{gen-DF}}$) is used for forests and POD$_{3.0,\text{gen-CR}}$ (or AF$_{st}$3$_{\text{gen-CR}}$) is used for crops.

2 Emissions
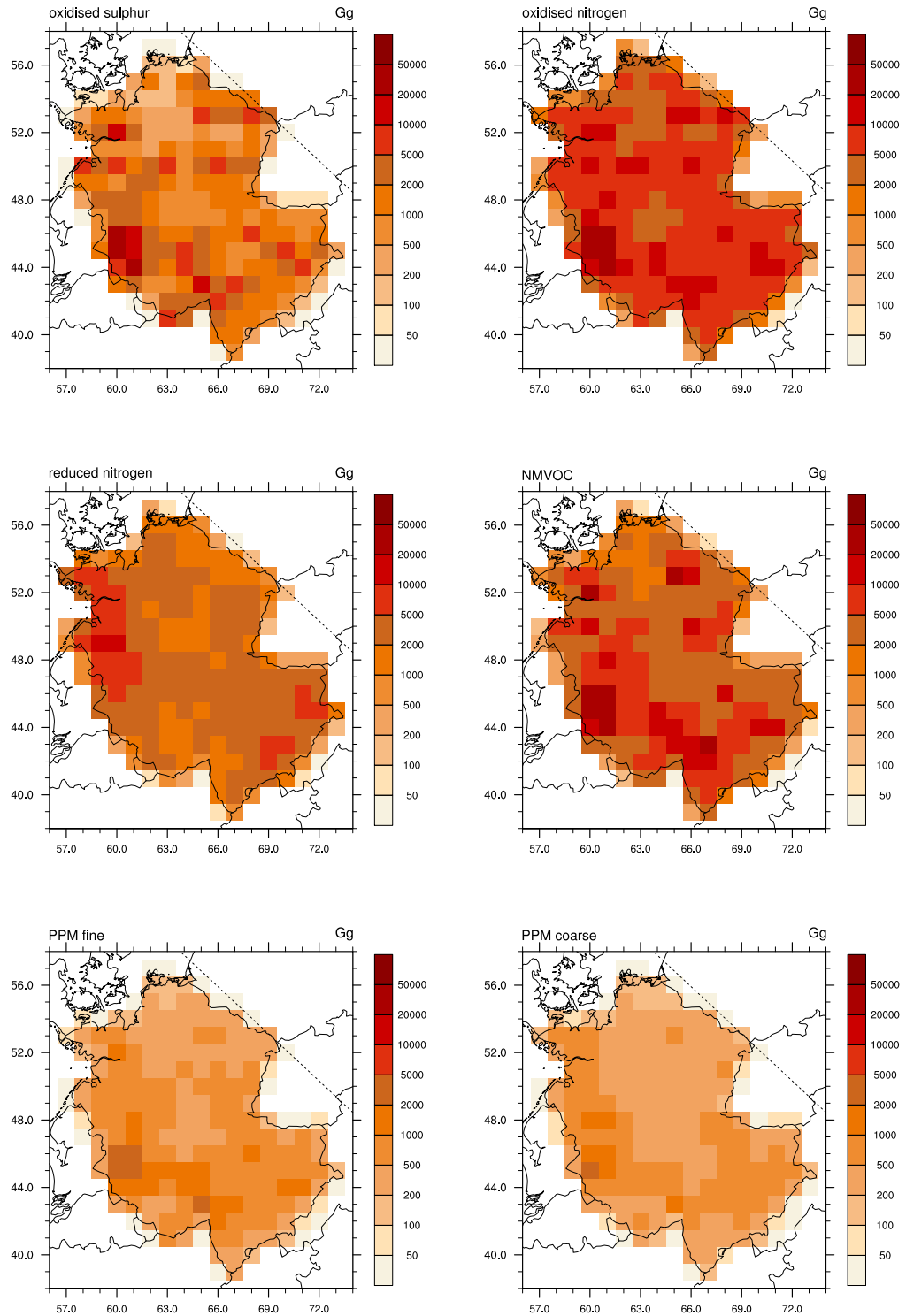
Figure 1: Spatial distribution of emissions from Germany in 2010.

3 Trends

Important: For correct interpretation of the results shown in this chapter please read the paragraph on *Trends* in Section 1.1.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2020
SO_x	653	643	590	573	547	517	520	497	490	435	449	409
NO_x	1925	1848	1768	1713	1650	1578	1564	1491	1418	1321	1323	963
NH_3	602	608	596	590	582	573	569	567	568	576	548	545
NMVOC	1391	1290	1229	1163	1175	1144	1132	1070	1017	931	1053	995
CO	4810	4604	4314	4117	3879	3659	3579	3482	3396	3011	3332	
$PM_{2.5}$	143	140	134	130	126	121	119	114	110	106	111	90
PM_{10}	240	234	225	218	214	207	206	201	195	187	193	153

Table 2: Emissions from Germany. Unit: Gg.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2020
S dep.	324	312	306	249	269	262	240	245	214	198	200	184
oxN dep.	292	278	280	245	256	256	250	239	217	217	218	164
redN dep.	370	372	362	318	344	342	339	338	329	344	325	325

Table 3: Estimated deposition of Sulphur (S) and Nitrogen (N) in Germany. Unit: Gg(S) or Gg(N).

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2020
mean ozone	32	31	34	33	32	33	34	33	32	32	32	34
max ozone	42	41	44	44	42	43	44	42	41	42	41	43
$AOT40_f^{uc}$	25366	21873	30004	31795	22369	21683	28508	21234	20639	21179	20717	18665
SOMO35	3094	2659	3621	3656	2837	2963	3318	2823	2722	2782	2721	2859
$POD_{1.0,gen}$-DF	35	33	37	33	33	32	34	33	33	34	30	32
$PM_{2.5}$ anthrop.	11	10	11	11	10	11	10	9	9	8	9	8
PM_{10} anthrop.	15	14	14	16	14	14	14	12	12	11	12	11

Table 4: Estimated yearly mean values of air quality indicators averaged over Germany. Unit: daily mean ozone (ppb), daily max ozone (ppb), $AOT40_f^{uc}$ (ppb·h), SOMO35 (ppb·d), $POD_{1.0,gen}$-DF (mmol/m2), $PM_{2.5}$ ($\mu g/m^3$) and PM_{10} ($\mu g/m^3$).
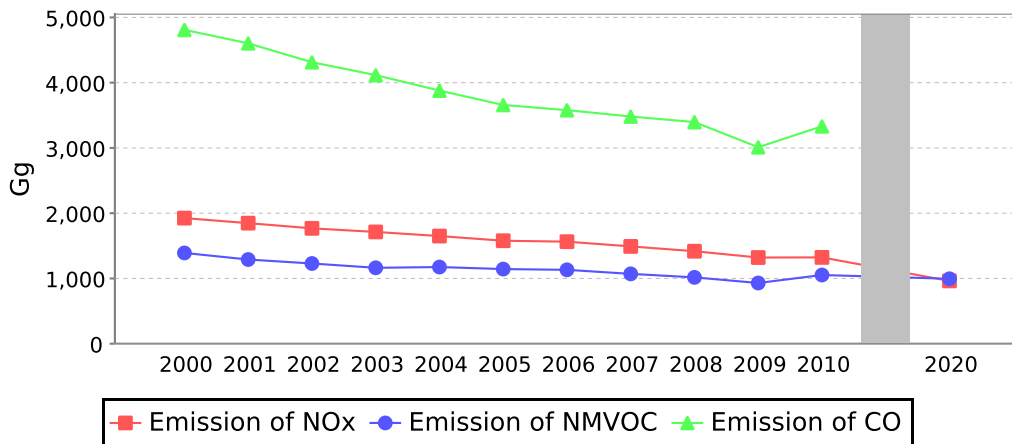
Figure 2: Trends in emissions of photo-oxidant pollution precursors. Unit: Gg (note that NO_x is here given as NO_2).
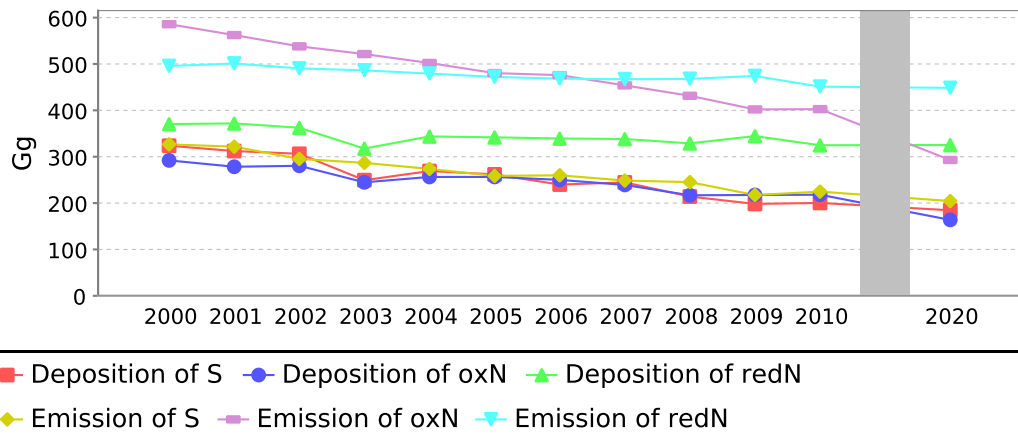
Figure 3: Trends in emissions and depositions of oxidised sulphur, oxidised nitrogen and reduced nitrogen. Unit: Gg(S) or Gg(N).
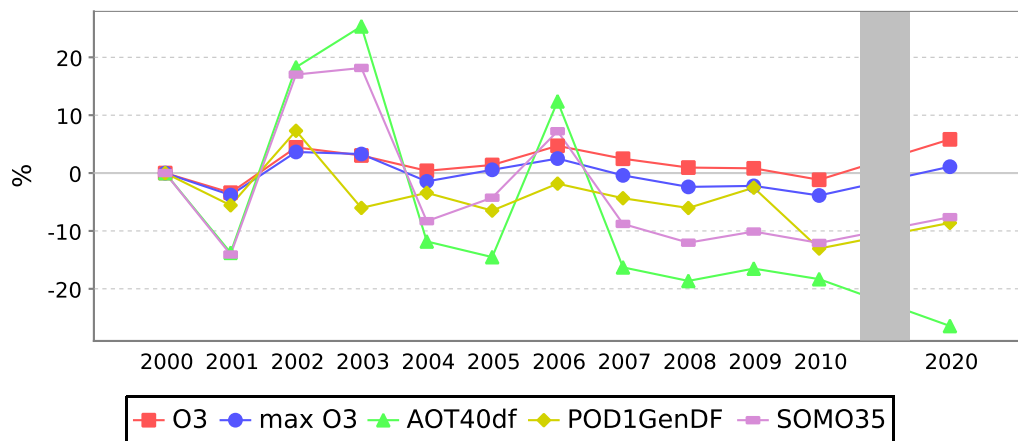
Figure 4: Changes in ozone related pollution relative to 2000. Unit: %. The large changes from year to year in some countries are mainly related to meteorological variability.
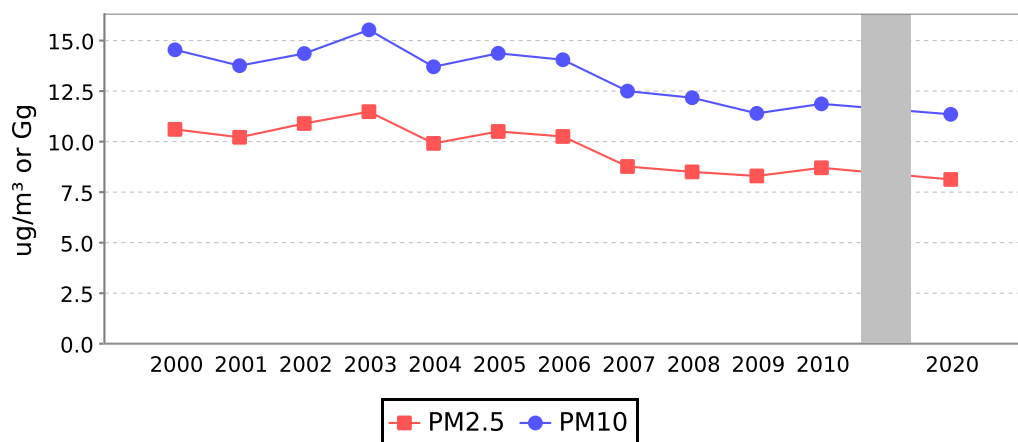

Figure 5: Trends in mean concentrations of particulate matter. Unit: $\mu g/m^3$.

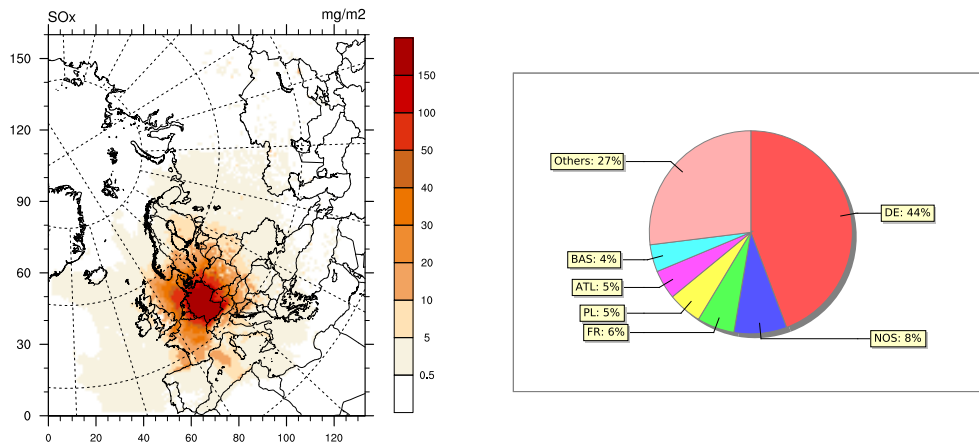# 4 Transboundary fluxes

4.1 Deposition of oxidised sulphur

Figure 6: Contribution of emissions from Germany to deposition of oxidised sulphur in the EMEP domain. Unit: mg(S)/m^2. The pie chart shows the six main receptor areas where oxidised sulphur from Germany is deposited. Unit: %.
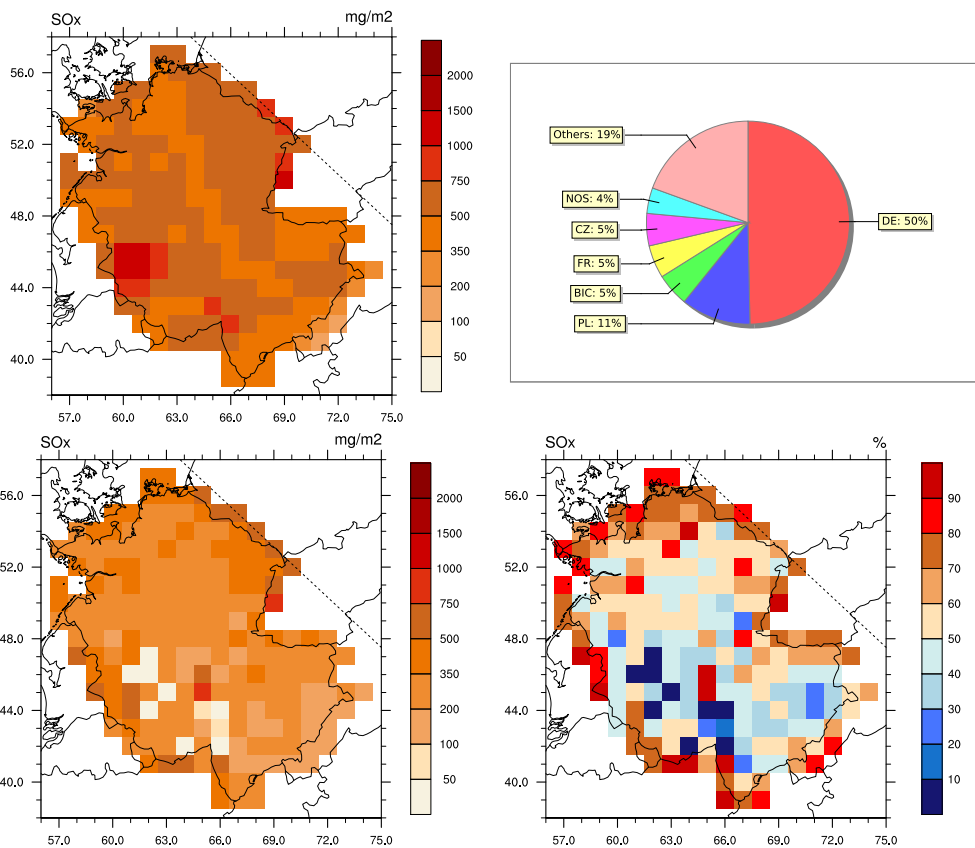
Figure 7: Top left: Deposition of oxidised sulphur in Germany. Unit: mg(S)/m^2. Top right: The six main contributors to oxidised sulphur deposition in Germany. Unit: (%). Bottom left: Oxidised sulphur deposition from transboundary sources. Unit: mg(S)/m^2. Bottom right: Fraction of transboundary contribution to total deposition. Unit: %.

4.2 Deposition of oxidised nitrogen
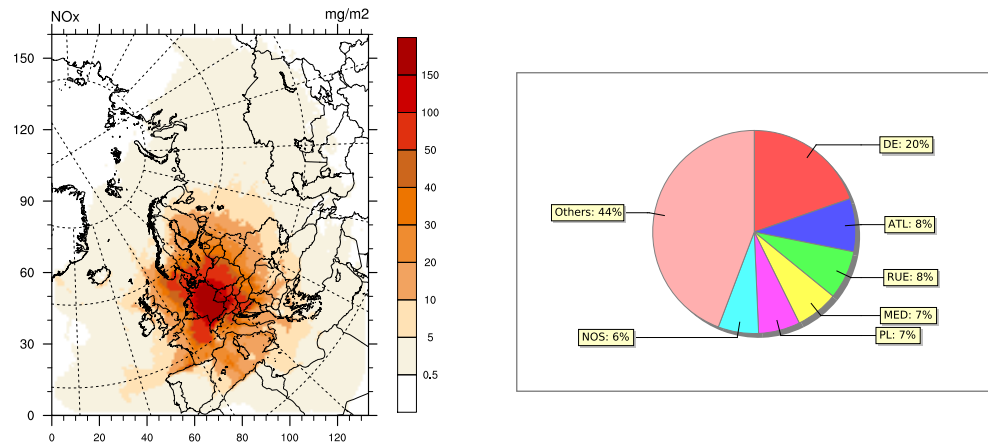
Figure 8: Contribution of emissions from Germany to deposition of oxidised nitrogen in the EMEP domain. Unit: mg(N)/m^2. The pie chart shows the six main receptor areas where oxidised nitrogen from Germany is deposited. Unit: %.
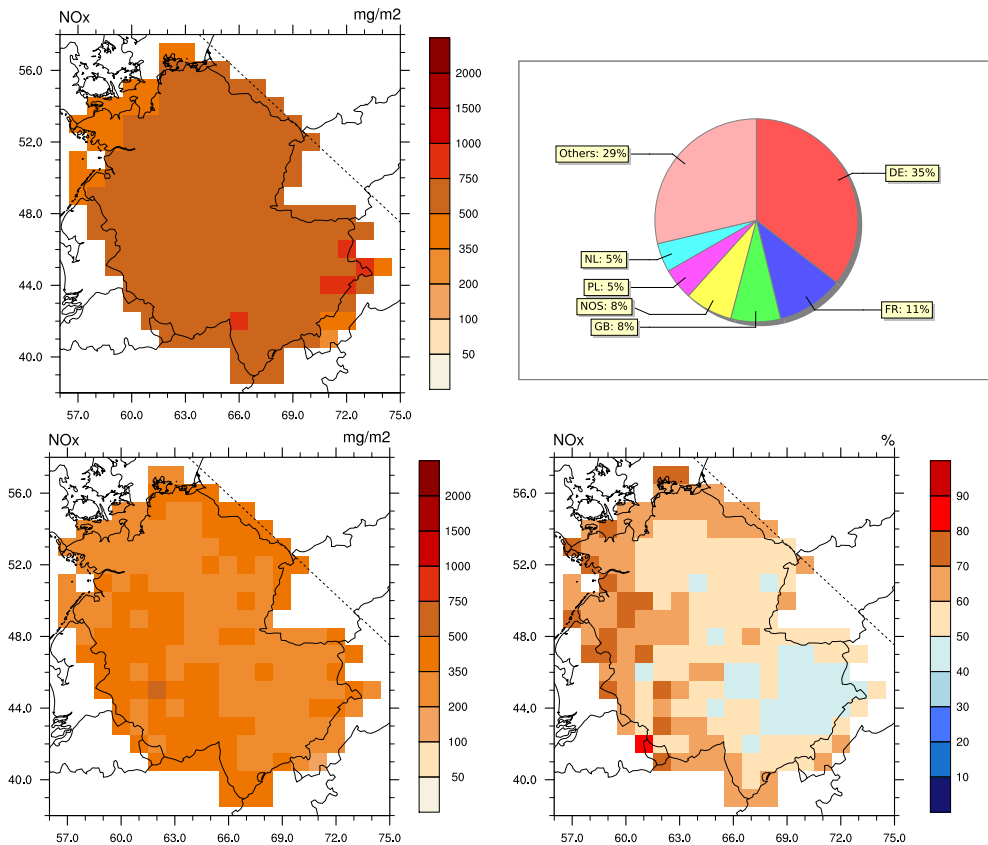
Figure 9: Top left: Deposition of oxidised nitrogen in Germany. Unit: mg(N)/m^2. Top right: The six main contributors to oxidised nitrogen deposition in Germany. Unit: %. Bottom left: Oxidised nitrogen deposition from transboundary sources. Unit: mg(N)/m^2. Bottom right: Fraction of transboundary contribution to total deposition. Unit: %.

4.3 Deposition of reduced nitrogen
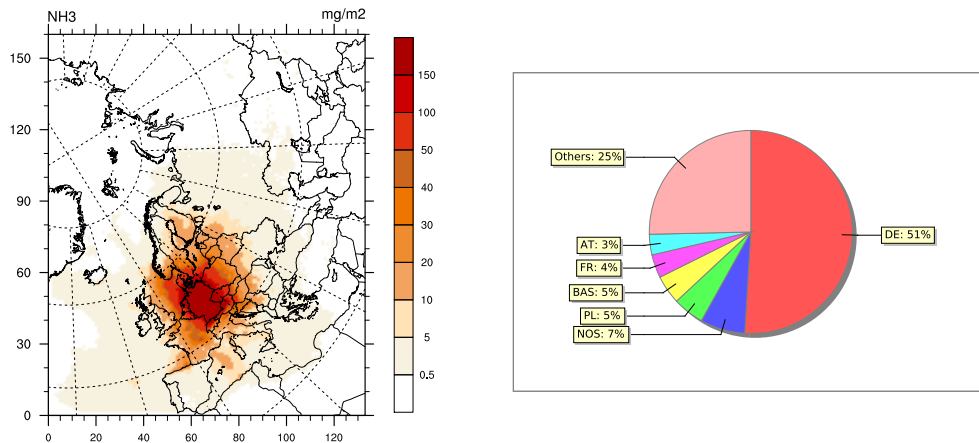
Figure 10: Contribution of emissions from Germany to deposition of reduced nitrogen in the EMEP domain. Unit: mg(N)/m^2. The pie chart shows the six main receptor areas where reduced nitrogen from Germany is deposited. Unit: %.
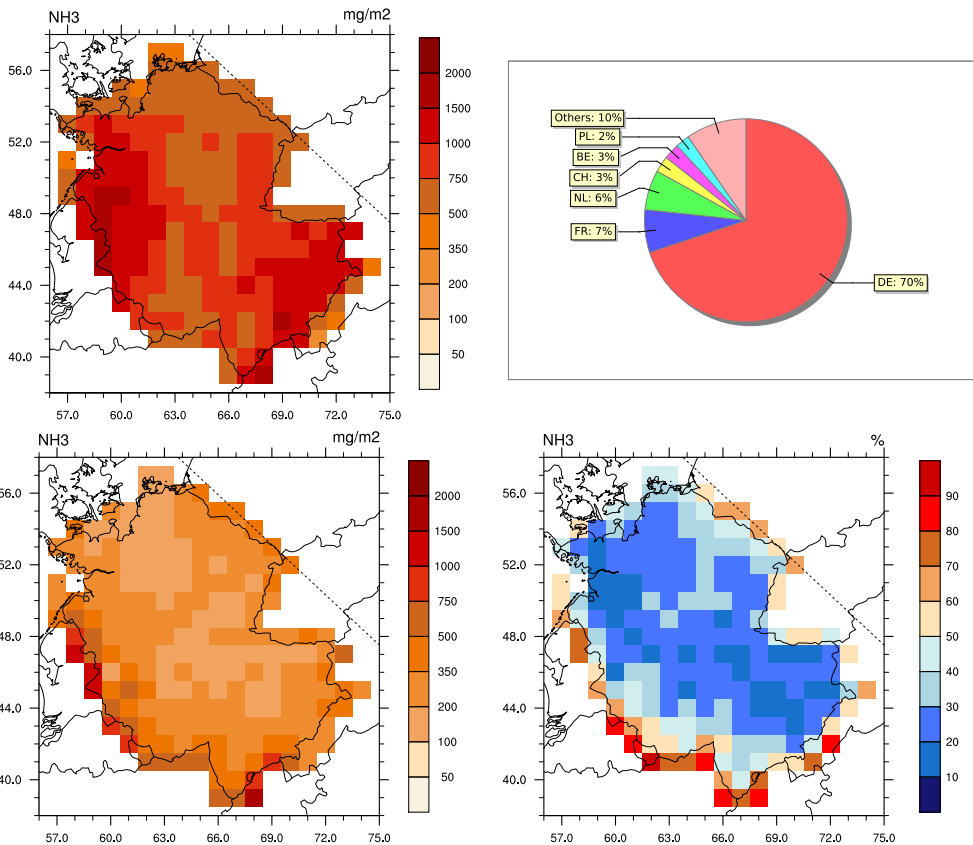
Figure 11: Top left: Deposition of reduced nitrogen in Germany. Unit: mg(N)/m^2. Top right: The six main contributors to deposition of reduced nitrogen in Germany. Unit: %. Bottom left: Deposition of reduced nitrogen from transboundary sources. Unit: mg(N)/m^2. Bottom right: Fraction of transboundary contribution to total deposition. Unit: %.

5 Transboundary concentrations of ozone

5.1 AOT40$_f^{\text{uc}}$
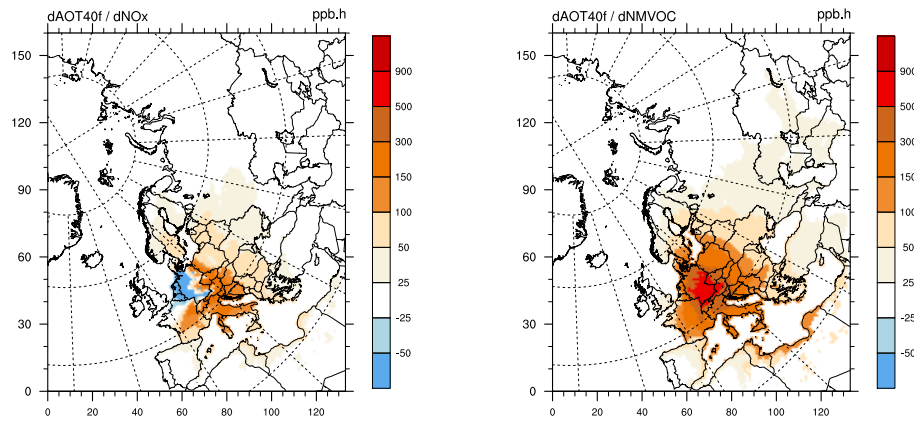
Figure 12: Reduction in AOT40$_f^{\text{uc}}$ that would result from a 15% reduction in emissions of NO$_x$ (left) and NMVOC (right) from Germany. Unit: ppb·h.
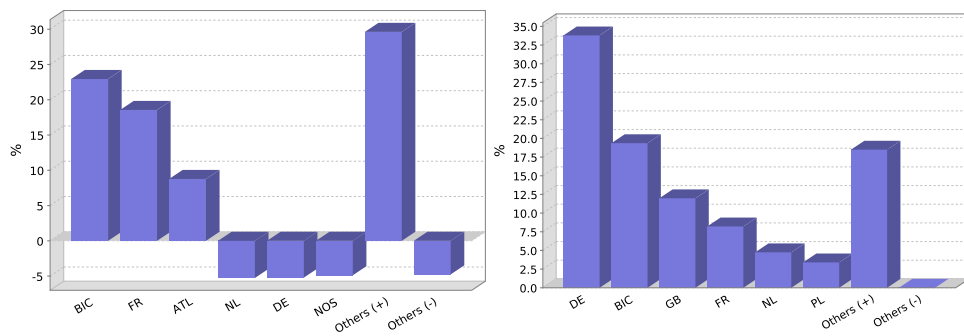
Figure 13: Six most important contributors to AOT40$_f^{\text{uc}}$ in Germany related to emissions of NO$_x$ (left) and NMVOC (right). Unit: %.
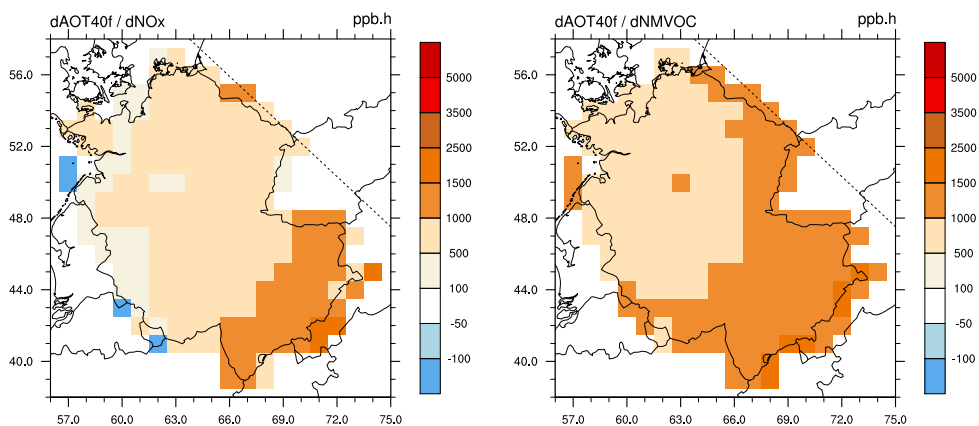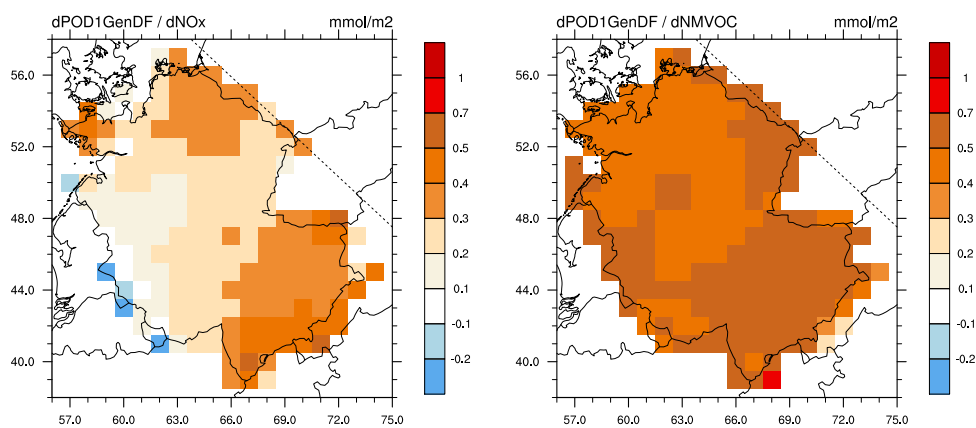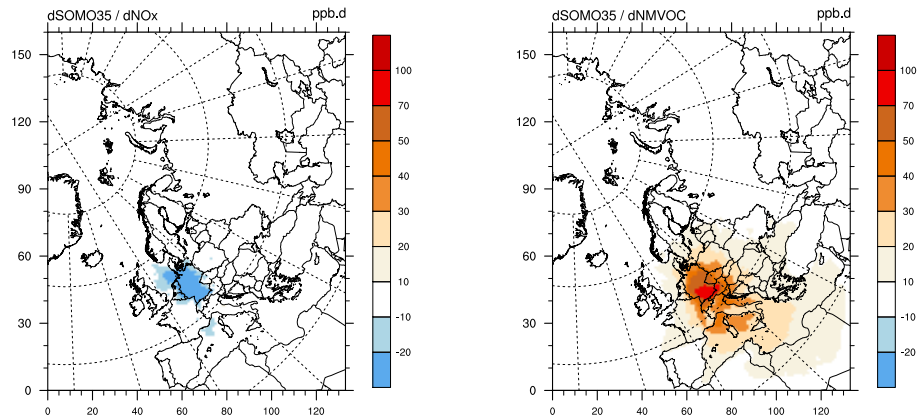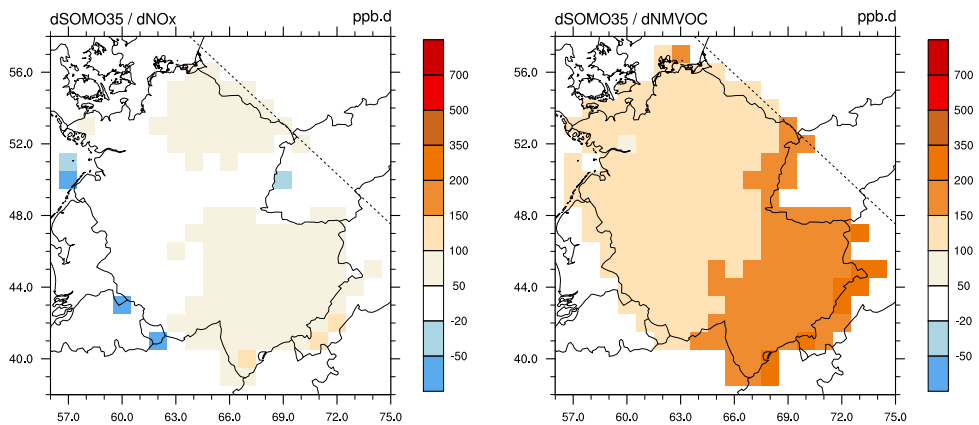

Figure 14: Reduction in AOT40$_f^{\text{uc}}$ that would result from a 15% reduction in emissions of NO$_x$ (left) and NMVOC (right) outside Germany. Unit: ppb·h.

5.2 POD$_{1.0,\text{gen-DF}}$ – Ozone fluxes to deciduous forests
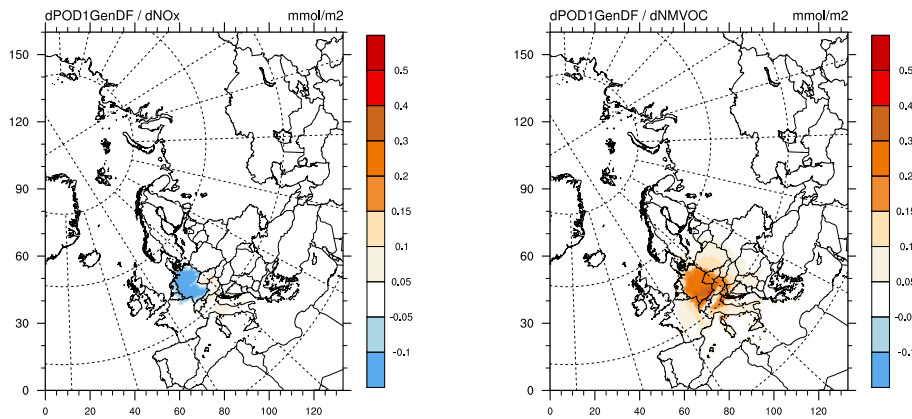
Figure 15: Reduction in POD$_{1.0,\text{gen-DF}}$ that would result from a 15% reduction in emissions of NO$_x$ (left) and NMVOC (right) from Germany. Unit: mmol/m^2.
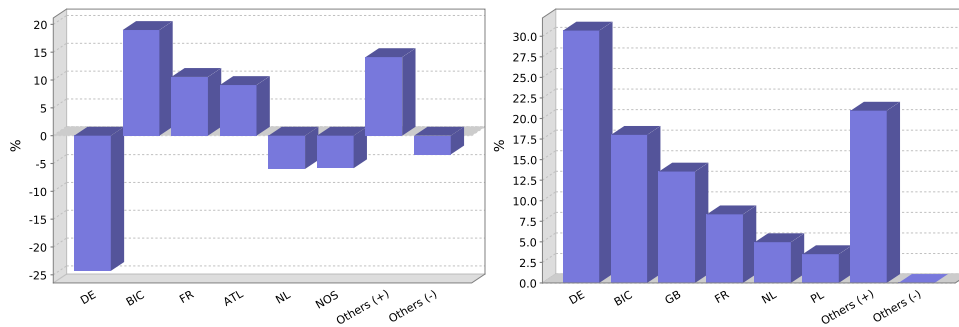
Figure 16: Six most important contributors to POD$_{1.0,\text{gen-DF}}$ in Germany related to emissions of NO$_x$ (left) and NMVOC (right). Unit: %.

Figure 17: Reduction in POD$_{1.0,\text{gen-DF}}$ that would result from a 15% reduction in emissions of NO$_x$ (left) and NMVOC (right) outside Germany. Unit: mmol/m^2.

5.3 SOMO35 – Risk of ozone damages to human health

Figure 18: Reduction in SOMO35 that would result from a 15% reduction in emissions of NO_x (left) and NMVOC (right) from Germany. Unit: ppb·day.
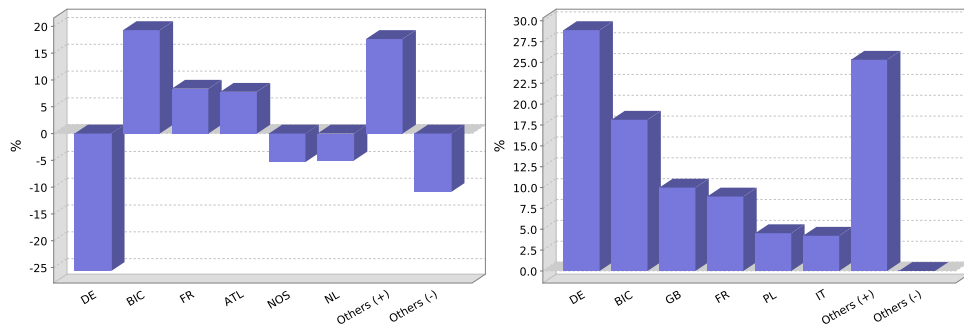
Figure 19: Six most important contributors to SOMO35 in Germany related to emissions of NO_x (left) and NMVOC (right). Unit: %.

Figure 20: Reduction in SOMO35 that would result from a 15% reduction in emissions of NO_x (left) and NMVOC (right) outside Germany. Unit: ppb·day.

6 Transboundary concentrations of particulate matter
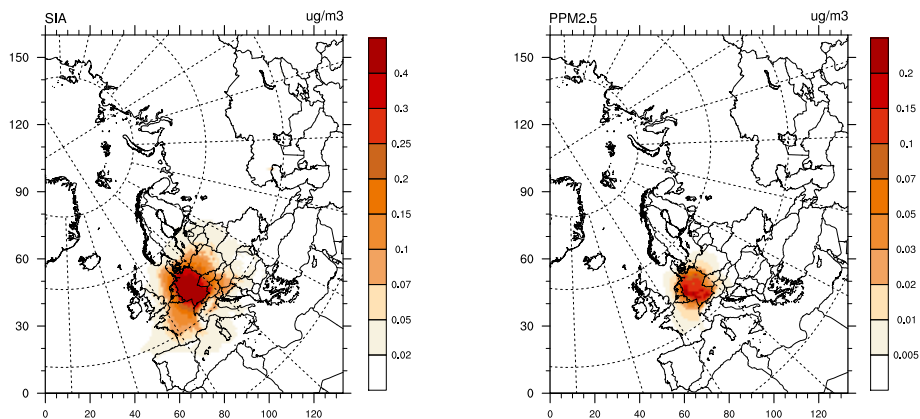
Figure 21: Reduction in concentrations of SIA (left) and PPM2.5 (right) that would result from a 15% reduction in emissions from Germany. Unit: $\mu g/m^3$. Note the difference in scales.
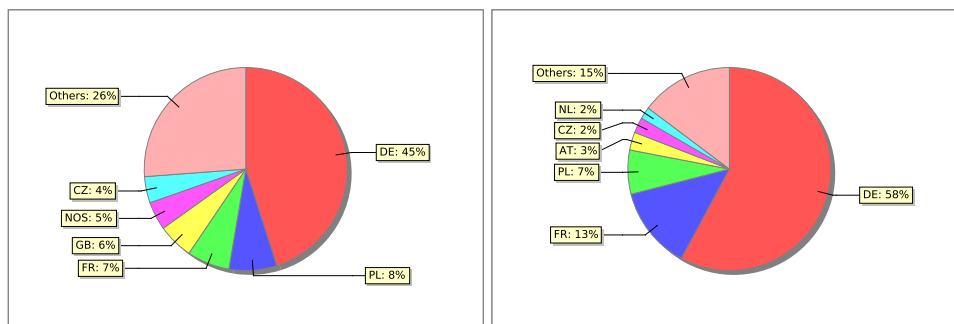
Figure 22: Main contributors to concentrations of SIA (left) and PPM$_{2.5}$ (right) in Germany. Unit: %.
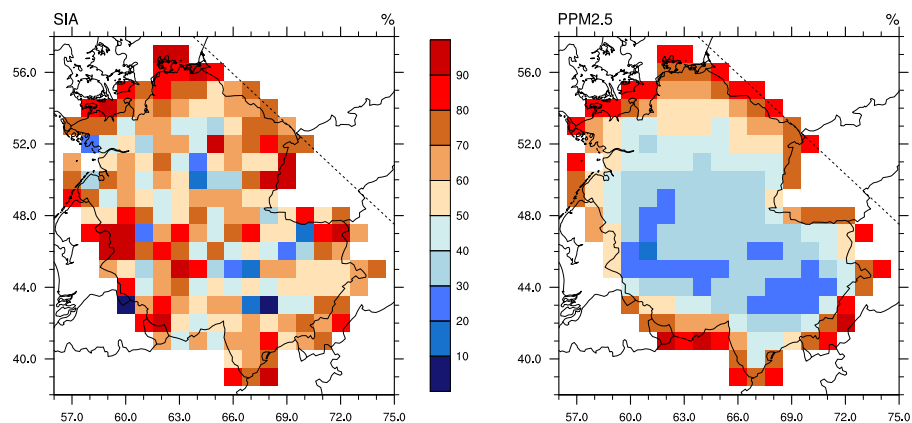
Figure 23: Fraction of transboundary contributions to concentrations of SIA (left) and PPM$_{2.5}$ (right) in Germany. Unit: %.
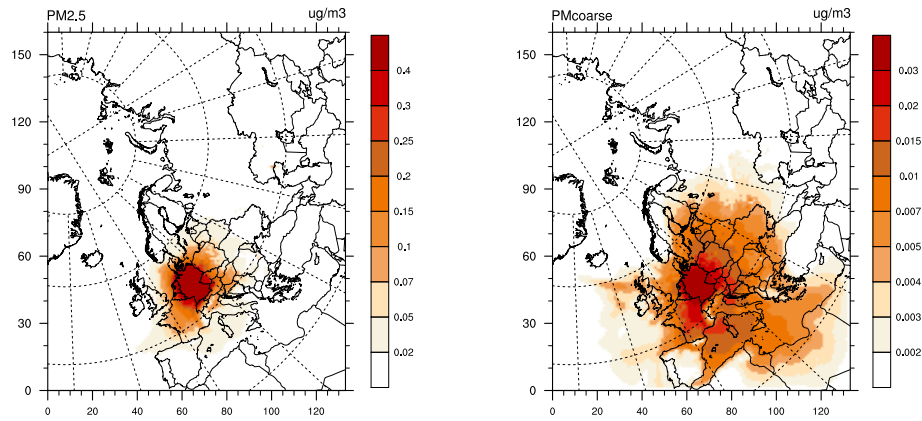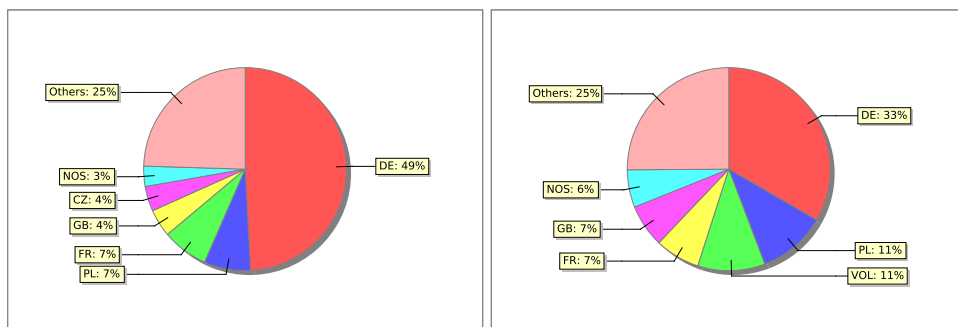
Figure 24: Reduction in PM$_{2.5}$ and PM$_{coarse}$ concentrations that would result from a 15% reduction of emissions from Germany. Unit: μg/m^3. Note the different color scales.

Figure 25: Main contributors to concentrations of PM$_{2.5}$ (left) and PM$_{coarse}$ (right) in Germany. Unit: %.
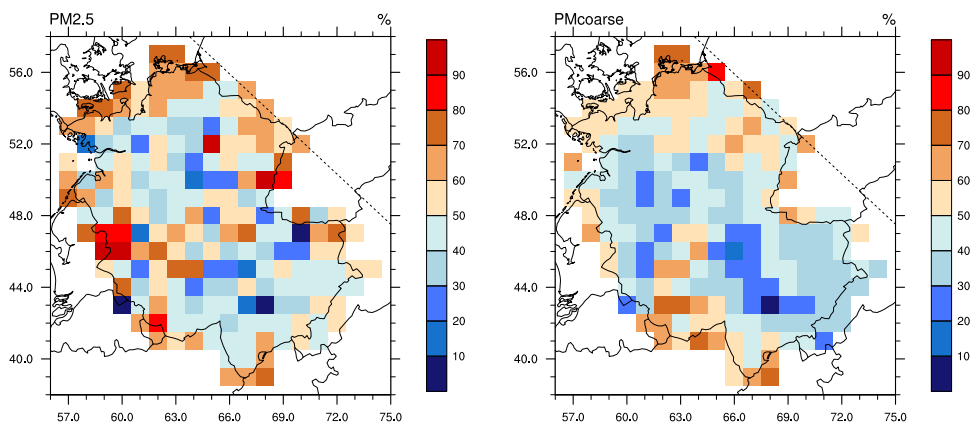

Figure 26: Fraction of transboundary contributions to PM$_{2.5}$ and PM$_{coarse}$ concentrations in Germany. Unit: %.
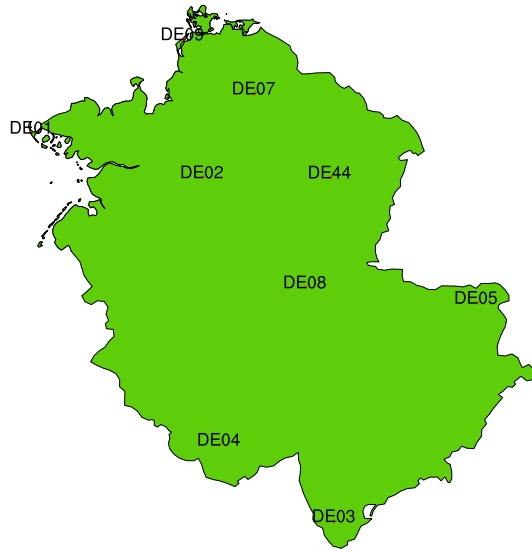
7 Comparison with observations

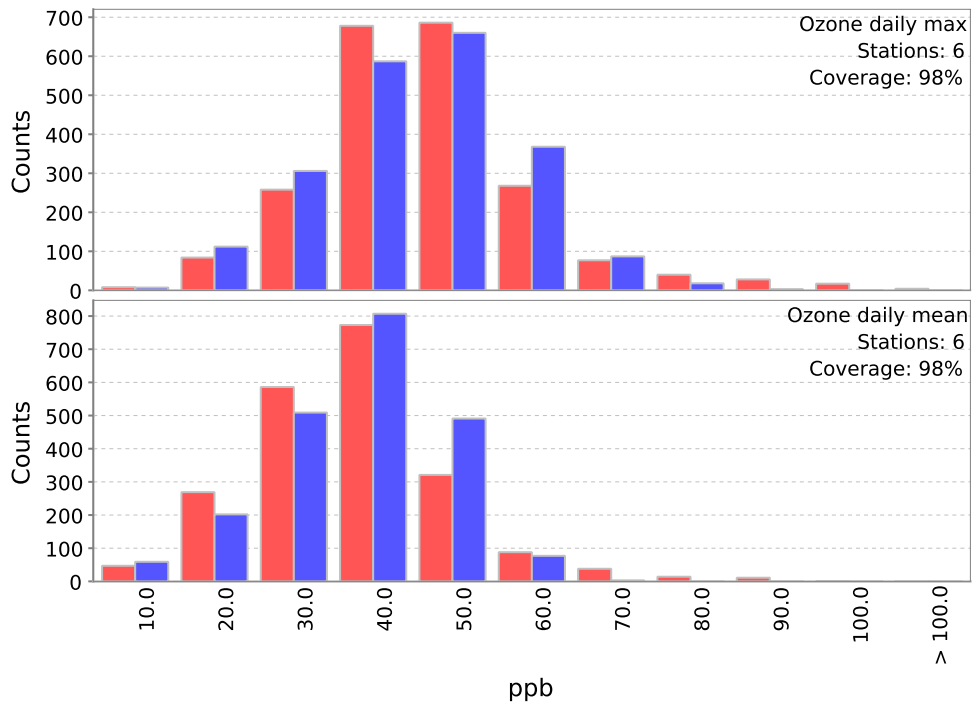Figure 27: Location of stations in Germany.

Figure 28: Frequency analysis of ozone in Germany at the stations that reported O_3 for 2010 (Model, Observations).
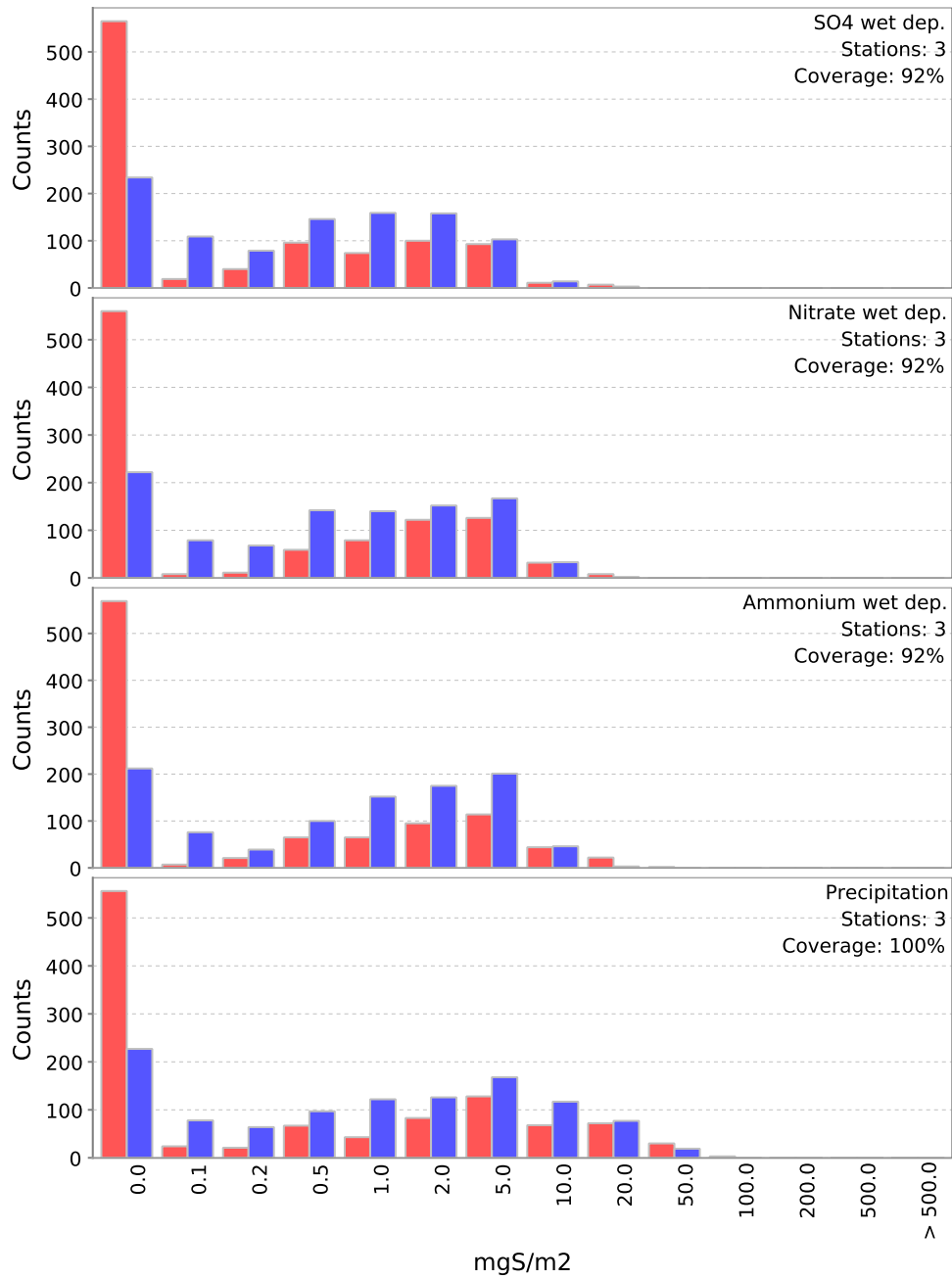
Figure 29: Frequency analysis of depositions in precipitation in Germany (Model, Observations).
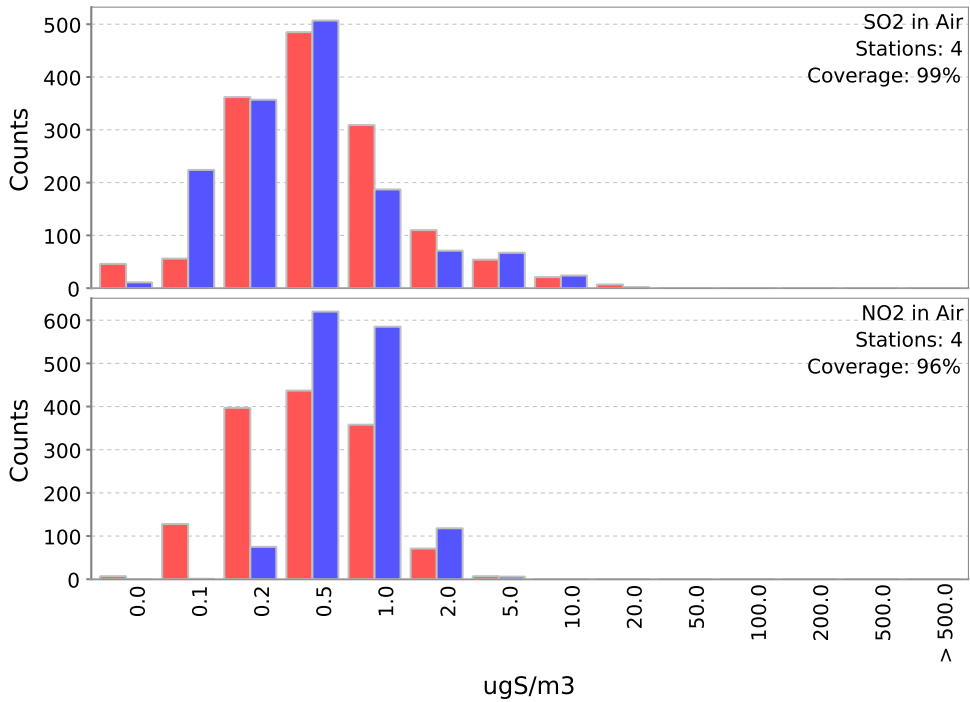
Figure 30: Frequency analysis of air concentrations in Germany (Model, Observations).

Component	No.	Bias	Correlation	RMSE
SO2 in Air	4	-15%±4%	0.93±0.19	0.40±0.11
Sulfate in Air	0			
NO2 in Air	4	37%±37%	0.82±0.09	1.08±0.13
NO3- in Air	0			
NH3+NH4+ in Air	0			
Ozone daily max	6	-3%±5%	0.84±0.04	6.60±1.59
Ozone daily mean	6	1%±11%	0.80±0.05	6.59±1.44
SO4 wet dep.	7	30%±47%	0.33±0.16	5.96±0.92
Nitrate wet dep.	7	12%±36%	0.46±0.16	6.91±1.02
Ammonium wet dep.	7	1%±29%	0.50±0.11	9.77±2.31
Precipitation	7	11%±29%	0.70±0.18	15.26±4.66

Table 5: Annual statistics of comparison of model results with observations in Germany for stations with a sufficiently consistent set of data available in weekly or higher time-resolution. Standard deviations provide variability ranges between stations.

8 Risk of damage from ozone and particulate matter in Germany
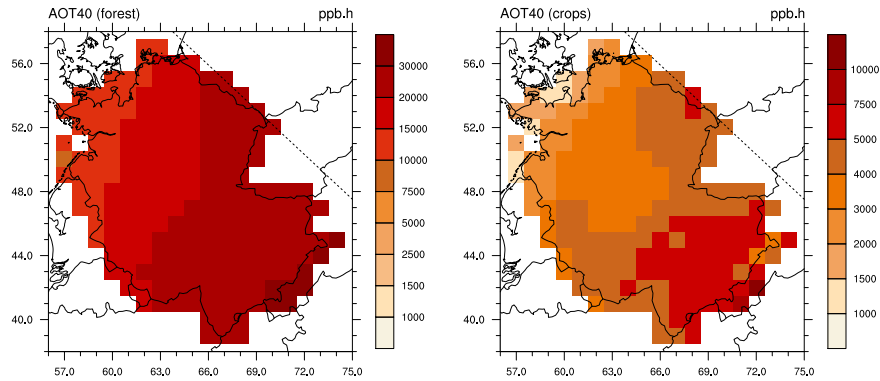
8.1 Ecosystem-specific AOT40 values

Figure 31: AOT40$_f^{uc}$ and AOT40$_c^{uc}$ in Germany in 2010. *(AOT40$_f^{uc}$: growing season April-Sept., critical level for forest damage = 5000 ppb·h; AOT40$_c^{uc}$: growing season May-July, critical level for agricultural crops = 3000 ppb·h.)*
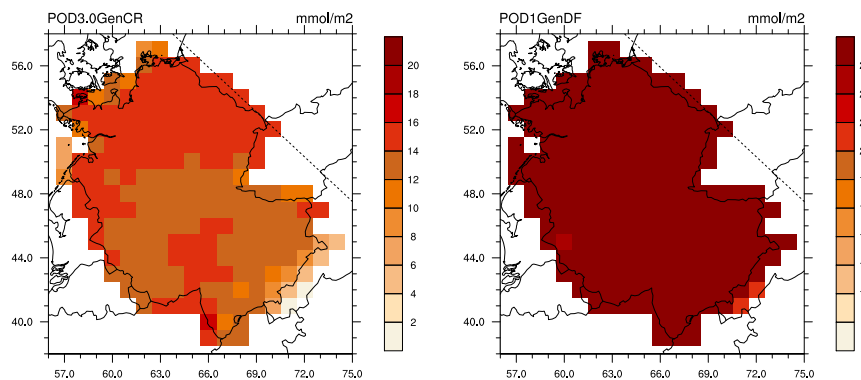
8.2 Ecosystem-specific ozone fluxes

Figure 32: POD$_{3.0,gen\text{-}CR}$ and POD$_{1.0,gen\text{-}DF}$ in Germany in 2010.

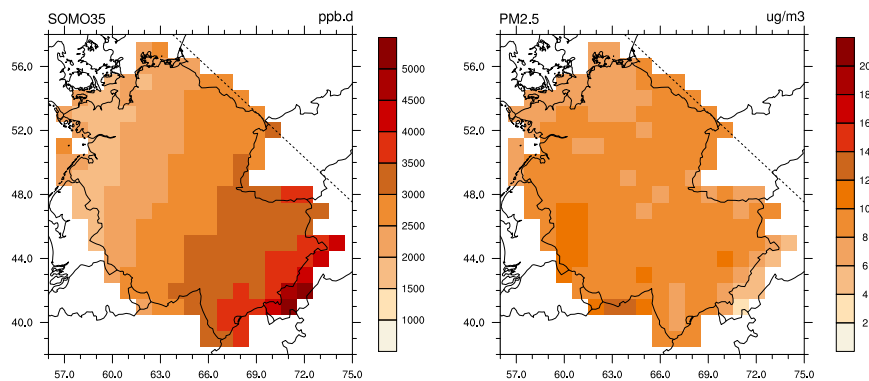## 8.3 Health impacts from ozone and particulate matter

Figure 33: Regional scale SOMO35 and PM$_{2.5}$ in Germany in 2010.